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A STRESS-TEST EVALUATION OF DISEASE FORECASTING FOR MANAGING POTATO LATE BLIGHT

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ABSTRACT

In an effort to prevent potato late blight, most potato growers in New York apply fungicides on a regular schedule. An alternative to regular prescheduled applications is to apply fungicides according to forecasts of disease, such as those provided by Blitecast. In previous studies, prescheduled and forecast decision rules have been compared on farms and in experimental plots. The comparisons on farms are inconclusive because of the infrequency of detectable late blight in commercially managed potatoes and the number of contributing factors when the disease does occur. Experimental plots provide stress-test comparisons of the relative effectiveness of prescheduled and forecast rules but are not appropriate for estimating crop losses that might result from these rules on farms.

In this study, prescheduled and forecast rules were compared in two ways using simulation experiments as stress-tests of relative effectiveness. With the first method, the decision rules were compared in terms of number of fungicide applications while holding constant the level of disease. With the second method, costs and crop losses for the two rules were estimated using the experimental results in combination with information about the cost of late blight on farms. In these stress-test comparisons using the simulation model, the prescheduled spray rules performed as well as or better than disease forecasting based on Blitecast.

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DISEASE FORECASTING FOR MANAGING POTATO LATE BLIGHT

by

G.R. Fohner, G.B. White, and W.E. Fry*

INTRODUCTION

Potato late blight, induced by the fungus Phytophthora infestans (Mont.) d By., is economically important in the management of potatoes in New York State because of the crop losses it can cause and the cost of efforts to prevent those losses. Most potato growers in New York apply fungicides regularly in an effort to prevent the disease, because once initiated it may spread rapidly and cause yield loss, blighted tubers, and losses in storage.

An alternative to the common practice of spraying regularly at prescheduled intervals is provided by Blitecast (Krause et al.), which uses measurements of rainfall, temperature, and relative humidity to forecast the incidence of late blight and to schedule fungicide sprays. The objective of Blitecast is to control late blight more effectively or with fewer fungicide sprays than spraying at prescheduled intervals. Since sprays are scheduled using information about past and current conditions rather than forecasts of weather, Blitecast results in sprays after conditions have been favorable for disease, rather than before. The rationale for this approach is to slow the subsequent increase in undetected disease (MacKenzie). The Blitecast decision rule is perhaps best viewed as a means of allocating fungicides among growing seasons and parts of seasons according to favorability for blight.

In previous studies, the performance of Blitecast has been assessed by comparing it with regular sprays at prescheduled intervals in commercial fields and experimental plots. Since prescheduled sprays almost always prevent detectable late blight in commercial potato fields (Table 1 and Appendix A), Blitecast has been evaluated in commercial fields according to whether it prevents late blight using fewer sprays than the decision rule calling for regular, prescheduled sprays (Andaloro, Weekly Crop Reports 1961 and 1962[1], Krause). The conclusiveness of these comparisons in commercial fields is limited by the confounding effects of inoculum levels, weather, and differences among test sites. For example, a decision rule may successfully prevent late blight with fewer sprays in most years because inoculum is scarce or conditions are unfavorable for the disease, but may increase cost or risk in the long run by increasing crop losses in years favorable for disease.

To insure that decision rules are actually tested, controlled field experiments in which inoculum is plentiful and conditions are favorable for disease may be used (Appendix B). Such experiments may be interpreted best as stress tests, comparisons of decision rules under conditions that insure that the rules are tested and the differences among them are enhanced.

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TABLE 1.

Summary of Reported Late Blight in Upstate New York 1960-1980

Number of Years	Reported Incidence and Severity of Disease
7	no reports of late blight in commercial fields
5	one occurrence of late blight; no indication of significant loss
5	late blight in more than one field but confined to a few locales; indication of significant crop loss in at least one field in two of the five years
4	late blight common throughout upstate New York; indication of significant crop loss in at least one field in three of the four years

Source: Weekly Report on Insects, Diseases, and Crop Development. Cooperative Extension, Cornell University, Ithaca, NY 14853-0398. (For a summary of yearly reports, see Appendix A.)

This experimental situation is efficient for obtaining information about the relative effectiveness of the decision rules but is not representative of commercial potato fields, in which the pathogen may be rare and conditions often may be unfavorable for the disease.

Stress-test experiments have been used in two ways to compare decision rules for controlling late blight. In one approach, severities of disease observed for the alternative decision rules have been compared statistically to test hypotheses of no difference (Krause, Fry). A problem with this approach is that statistical and economic significance are not equivalent (Dillon). Differences that are economically significant may not be declared statistically significant if variability among replicates in stress tests reduces the power of the statistical tests. Conversely, differences in stress tests may have statistical significance but not economic significance because the differences are magnified by the conditions of the stress test, and measures of disease such as percent defoliation may not be directly related to the costs of disease.

The other approach to using stress tests for comparisons has been to estimate the differences in crop loss from forecasting and prescheduled sprays (Bruhn and Fry). These estimates of crop losses in stress tests, however, are likely to be greater than the losses from forecasting and prescheduled sprays in commercial fields because conditions in the stress tests are uncommonly favorable for the disease. Also, once late blight is detected in a commercial field, decision rules for spraying are usually changed, so the disease and crop loss do not continue to increase as they do in experiments in which rules are not changed.

In this study, disease forecasting based on Blitecast was compared to regular, prescheduled sprays in a stress-test experiment using computer simulation. The objective was to perform the comparison using methods of analysis that were consistent with the characteristics of stress-test experiments, and with the difficulty of estimating the cost of disease.

PROCEDURES

The Model

The experiment was performed using a modified[2] version of simulation models of late blight (Bruhn et al.) and fungicide deposition and weathering (Bruhn, Bruhn and Fry), (Figure 1). Model specifications for the potato cultivar Katahdin were used in the experiment. All decision rules were evaluated for 10 simulated seasons using weather data recorded at Geneva, New York.

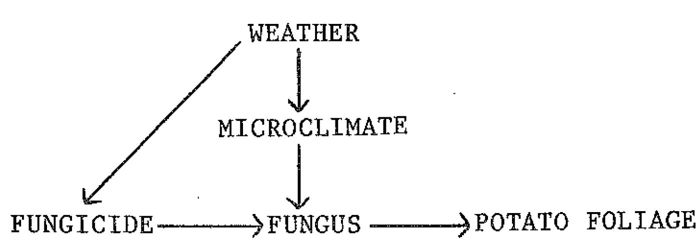


Figure 1. Components of the Simulation Model Used in the Experiment

Four characteristics of the model were especially important for interpreting the results.

1. The size of the area modeled in the experiment was 25 square meters, roughly comparable to plot size in field experiments, so the dispersal of the pathogen to initiate secondary foci of disease was not represented.

2. The natural processes by which inoculum might be introduced into a potato field were not modeled; the introduction and continued supply of inoculum from sources outside the test plot were imposed as initial conditions.[3]

3. Only late blight on the potato foliage was described; the infection of tubers was not included in the model.

4. The model was developed and validated using data primarily from field plots in which conditions were favorable for late blight.

Because of these characteristics, the simulation experiment was best interpreted as a stress test rather than as a model of commercial potato fields.

Methods of Analysis

To characterize the effectiveness of prescheduled and forecast decision rules, a range of rules was evaluated for both. For the prescheduled rules, 15 different spray intervals were evaluated, from spraying once every three days to spraying once every 17 days. For forecasting, five different forecast decision rules were evaluated. For all five, decisions about spraying were based on severity values and rain-favorable days, which are calculated in Blitecast using measurements of rainfall, temperature, and relative humidity. Blitecast was used as the intermediate forecast decision rule. Two forecasts that were more likely than Blitecast to call for sprays, and two that were less likely to call for sprays were derived by changing the severity value threshold at which sprays were recommended. This derivation was accomplished by shifting the Blitecast matrix relating severity values and spray recommendations (Table 2).

Using a range of decision rules for both prescheduled intervals and forecasting broadened the generality of the comparison between the two, and indicated the tradeoff between number of sprays and severity of diseases for each. Knowledge of this tradeoff permitted comparison of forecasting and prescheduled intervals at equal severity of disease, so knowledge of the relative costs of disease and sprays was not needed, and forecasting and prescheduled intervals could be compared on the basis of number of sprays alone.

In addition to comparing forecasting and prescheduled intervals at equal severities of disease, decision rules were compared using severity of disease in the simulation experiment to estimate relative effectiveness, then translating relative effectiveness into differences in cost using information about the cost of late blight on farms. Relative effectiveness was measured using frequency of high levels of disease and annual ratios of disease for the rules being compared.

TABLE 2.

Forecast Matrices Relating Severity Values (SV), Rain-Favorable Days (RFD), and Spray Recommendations

Forecast I

RFD During Previous 7 Days	SV During Previous 7 Days: <3	3	4	5	6	>6
	Message Number					
≤4	-1	-1	-1	-1	0	1
>4	-1	-1	-1	0	1	2

Forecast II

RFD During Previous 7 Days	<3	3	4	5	6	>6
	Message Number					
≤4	-1	-1	-1	0	1	1
>4	-1	-1	0	1	2	2

Forecast III
(Blitecast*)

RFD During Previous 7 Days	<3	3	4	5	6	>6
	Message Number					
≤4	-1	-1	0	1	1	2
>4	-1	0	1	2	2	2

Forecast IV

RFD During Previous 7 Days	<3	3	4	5	6	>6
	Message Number					
≤4	-1	0	1	1	2	2
>4	0	1	2	2	2	2

Forecast V

RFD During Previous 7 Days	<3	3	4	5	6	>6
	Message Number					
≤4	0	1	1	2	2	2
>4	1	2	2	2	2	2

Messages

-1: No spray
0: Update forecast in two days
1: 7-day spray schedule
2: 5-day spray schedule

*Krause, R.A., L.B. Massie, and R.A. Hyre. "Blitecast: a computerized forecast of potato late blight." Plant Disease Reporter 59(1975):95-98.

RESULTS

Comparing Decision Rules at Equal Severities of Disease

Results from the 10 simulated seasons for each of the five forecasts and 15 prescheduled intervals are shown in Figure 2. Severity of disease was measured as the percent defoliation from disease at the end of the season. Forecast III corresponds to standard Blitecast; forecasts IV and V resulted in increasingly more sprays than Blitecast, while forecasts II and I resulted in increasingly fewer sprays. The prescheduled intervals each correspond to a fixed number of sprays per season. For example, the prescheduled decision rule calling for sprays once every seven days resulted in 10 sprays per season. Some prescheduled spray intervals resulted in the same number of sprays as other intervals. The curve in Figure 2 passes through the points corresponding to the most effective prescheduled interval for that number of sprays.

The bars on the data points are standard errors of the sample average defoliation from disease. For clarity, error bars are drawn only for prescheduled intervals having points on the curve. The standard deviations for number of sprays for forecasts I through V were 1.491, 1.506, 1.449, 0.632, and 0.943. The number of sprays for each prescheduled interval was the same every season so standard deviations of number of sprays for these decision rules were zero.

The nearness of the forecasts to the prescheduled response curve in Figure 2 indicates that neither prescheduled spraying nor forecasting was clearly dominant in terms of controlling late blight in the simulation experiment[4]. Since forecasting requires information and management not required for prescheduled sprays, the results of this experiment imply that replacing prescheduled sprays with forecasting is unjustified.

The horizontal distance between the forecasts and the curve for prescheduled intervals is the difference in number of sprays resulting in the same severity of disease. Based on these horizontal distances, the relative performance of forecasting did not improve as the number of sprays decreased and disease increased. Factors that would encourage potato growers to accept greater occurrence of late blight, such as crop insurance or systemic fungicides able to eradicate late blight, therefore may favor widening of prescheduled spray intervals rather than forecasting.

The forecast data reported in Figure 2 resulted when forecasts were updated once every four days. The forecast decision rules also were tested using daily and weekly updates. The results of these tests are presented in Figure 3, along with those for the four day update and the prescheduled rules. In general, more frequent updating of forecasts improved their performance.

In all of the above results, disease was measured by percent defoliation from disease at the end of the season. This measure of disease does not reflect the timing of disease development throughout the season. Although this limitation may not be critical for experiments interpreted as stress tests of relative effectiveness, James and others (1974, 1979) have argued for the use of other measures of disease for studying crop loss. One

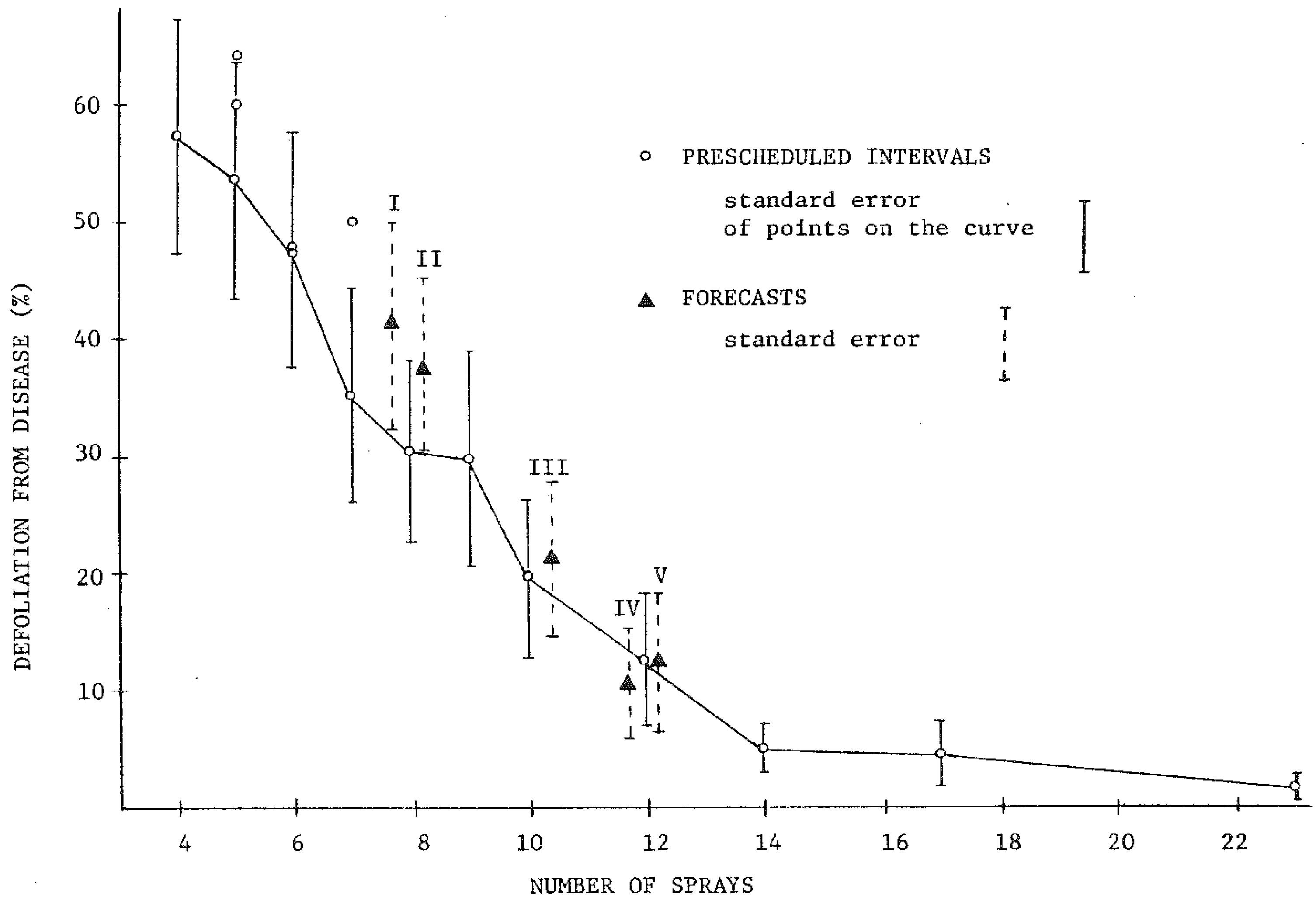


Figure 2. Defoliation from Disease and Number of Sprays: Ten-year Averages

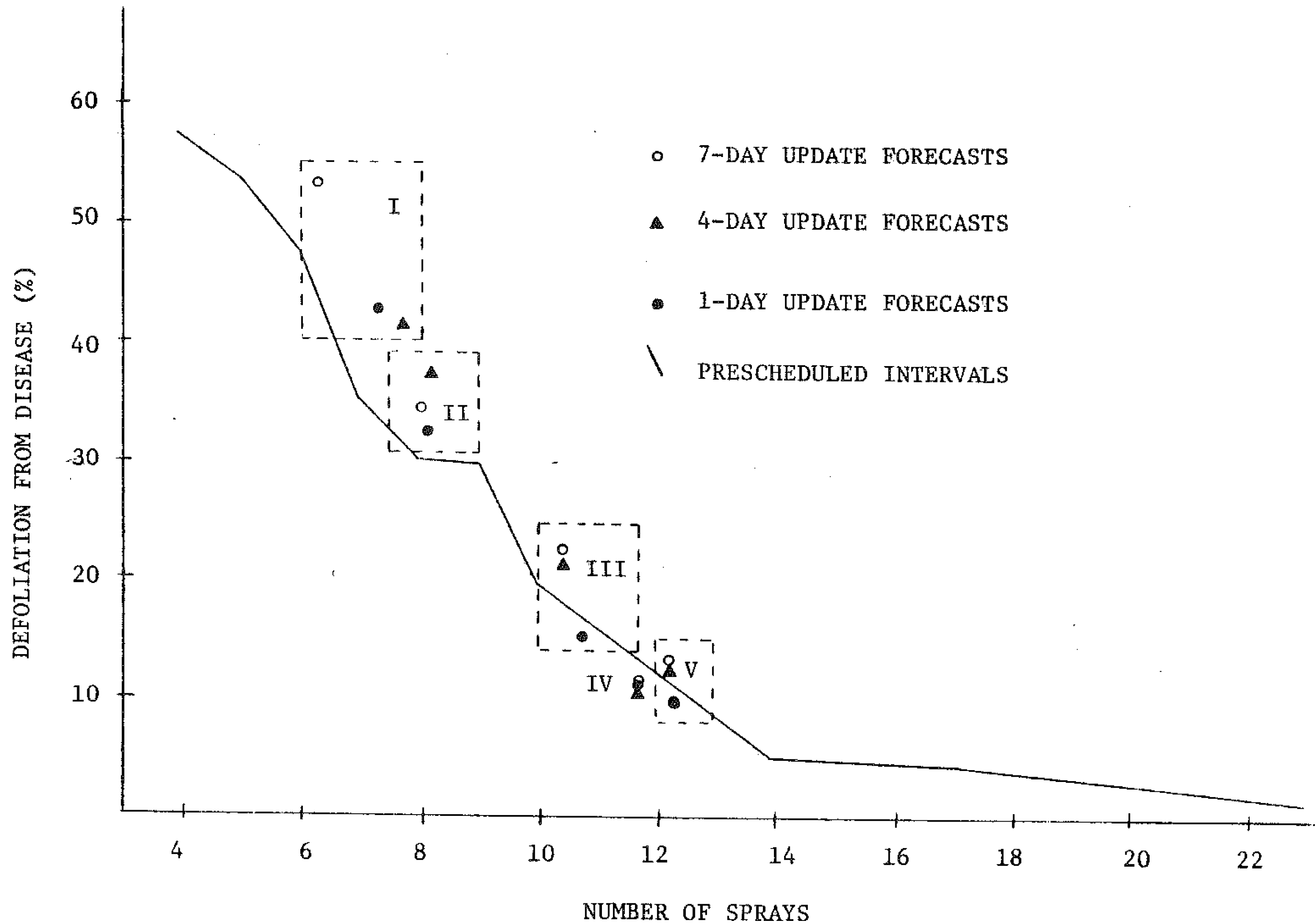


Figure 3. Frequency of Updating and Effectiveness of Forecasting: Defoliation from Disease and Number of Sprays: Ten-year Averages

measure of disease that does reflect the timing of disease development is the area under the disease progress curve (AUDPC) (James). Results for the prescheduled and forecasting decision rules (updated every fourth day) using AUDPC as the measure of disease again indicate that neither forecasting nor prescheduled intervals was clearly superior (Figure 4).

The prescheduled and forecast rules were also compared using two other measures: one that estimates percent loss of harvested tubers (James et al. 1972, MacKenzie and Petruzzo), and another that estimates percent loss of tubers of marketable size (James et al. 1973). Both measures are based on AUDPC with intervals under the progress curve weighted according to the stage of crop development. Since disease in the simulation experiment reflects the effectiveness of the decision rules in stress-tests rather than commercial conditions, the two measures of yield loss cannot be used directly to estimate the cost of disease. However, the measures can be used as indicators of relative effectiveness as legitimately as percent defoliation or AUDPC. The results using these two measures of disease were the same as those using final percent defoliation and AUDPC. Neither forecasting nor prescheduled intervals were clearly superior to the other.

Comparing Decision Rules At Unequal Severities of Disease

The comparison of forecasts with the curve for prescheduled intervals provides a useful general comparison of the prescheduled and forecast rules, but cannot be used to rank individual rules when one results in more sprays but less disease than another. To rank such rules, the dollar value of differences in disease must be estimated and used with differences in spray cost to provide a total comparison of costs. The severity of disease on potato foliage in the experiment cannot be used directly to estimate costs of disease because, in addition to overestimating the severity of disease for commercial conditions, it does not reflect the changes in fungicide use, harvesting, storage, and tuber quality that may result from an infestation of late blight. These changes may account for more of the cost of infestations of late blight than does yield loss from defoliation.

Although the experimental results are not appropriate for directly estimating the cost of disease associated with each decision rule, they can be used for this purpose if combined with information from potato growers about costs of late blight. For using this approach, the key step is selecting a statistic indicating the relative effectiveness of alternative decision rules in the experiment.

One possible statistic is average defoliation, the values reported in Figure 2. A comparison of the prescheduled seven-day rule and forecast III suggests problems with using these averages for indicating relative effectiveness. The 10-season averages for these two rules as shown in Figure 2 are 19.2 percent for the seven-day rule and 20.9 percent for forecast III. When these means were combined with results from 10 additional simulated seasons, the respective means were 16.5 percent and 18.6 percent (the standard deviations were 17.6 percent and 18.0 percent). Although the two rules resulted in comparable average defoliation, the distribution of seasonal values suggests that the commercial performance of the two rules may be

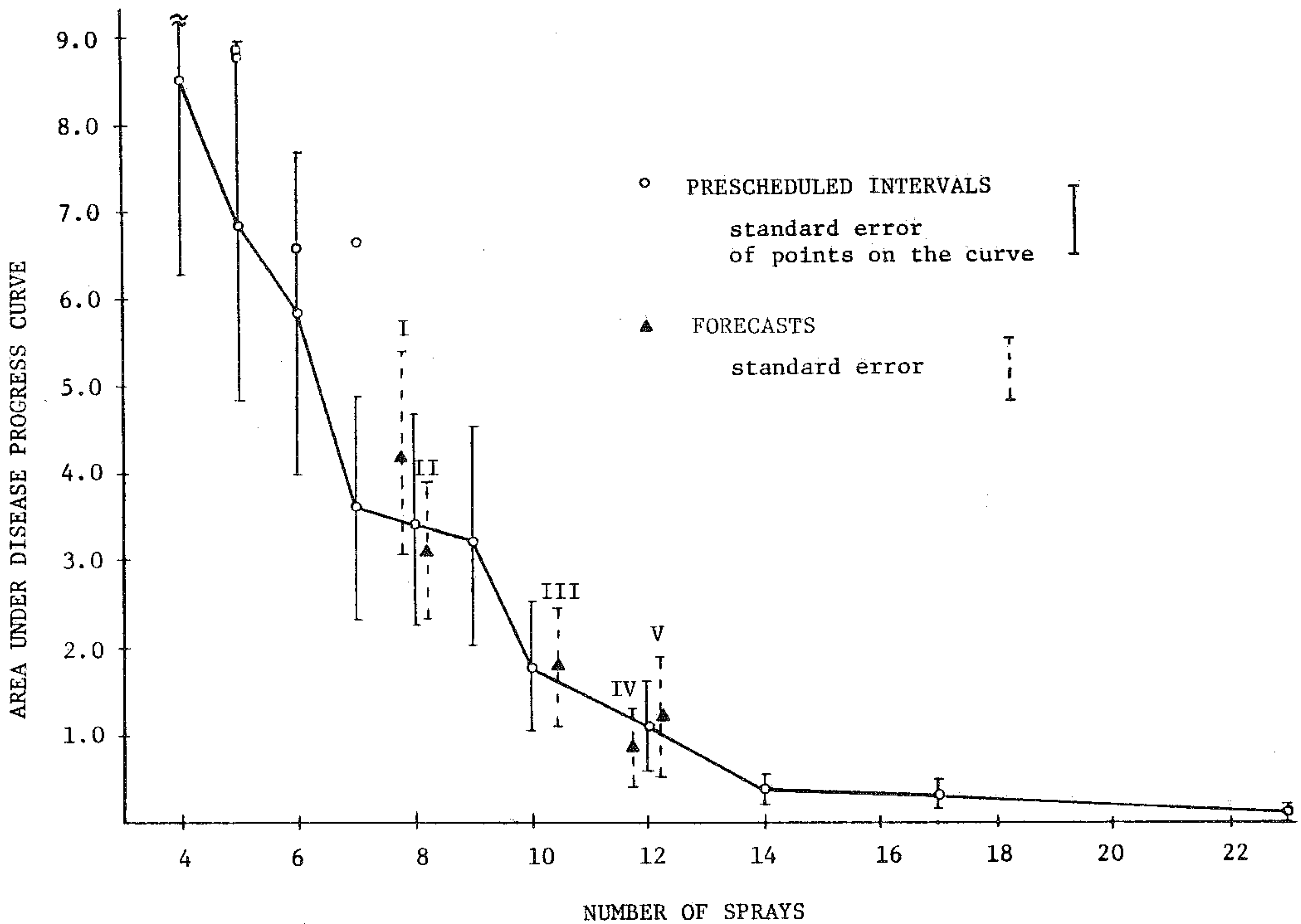


Figure 4. Area Under Disease Progress Curve and Number of Sprays: Ten-year Averages

different. In Figure 5, percent defoliation using the two rules are displayed for each of the 20 seasons over which the rules were tested.

The most notable differences between the observations for the two rules is the pair of seasons in which defoliation was low using the seven-day rule but high using forecast III, and one season in which the opposite was true. As indicators of relative effectiveness, these seasons with large differences may be more informative than the cumulative total of small differences in the other seasons. However, in the comparison of 20-season averages, these few large differences were largely masked by the sum of smaller differences. Also, averaging implies that the difference between 60 percent and 50 percent defoliation is as significant as that between 10 percent and 20 percent, although the relative effectiveness implied by the two pairs is different.

The interpretation of the annual observations as stress tests suggests an alternative statistic for indicating relative effectiveness. Suppose that past experience with the experimental model implied that holding defoliation from disease to below 20 percent indicated successful control in the stress test, and infestations of disease exceeding 20 percent defoliation indicated breakdowns in control. To compare forecast III and the seven-day interval, the ratio of number of breakdowns with each could be used to estimate the relative likelihood of infestations of late blight in commercial fields[5]. If the cost of an infestation of late blight that occurs when forecasting is used is comparable to the cost of an infestation with the seven-day interval, then the relative likelihood of infestations can be used to estimate relative costs from disease for the two rules. If expected cost of infestations of late blight using one of the decision rule can be estimated using information from potato growers, then the relative effectiveness indicated in the stress test could be used to estimate the expected cost for the other rule.

For example, suppose that while using a prescheduled seven-day spray interval a potato grower with 200 acres of potatoes has detected one infestation of late blight in 10 years, and that the infestation cost $6,000 in lost sales and increased management costs. This history of late blight can be used as the expected loss from late blight over 10 years using the seven-day interval. The expected loss from late blight using the forecast can be estimated as the ratio of breakdowns in the experiment for the forecast and prescheduled rules multiplied by the $6,000 cost using the prescheduled rule:

$$\frac{\text{(8 breakdowns using the forecast)}}{\text{(6 breakdowns using the prescheduled interval)}} * \$6{,}000 = \$8{,}000$$

With 200 acres of potatoes and a cost per spray of $8.00 per acre for fungicide and application, a reduction of only 1.25 sprays over 10 seasons using forecasting would match the added $2,000 expected costs from late blight.

These results are generalized in Figure 6, which indicates the breakeven line along which a reduction in spray cost would equal the added expected cost from late blight. The slope of the breakeven line is the relative

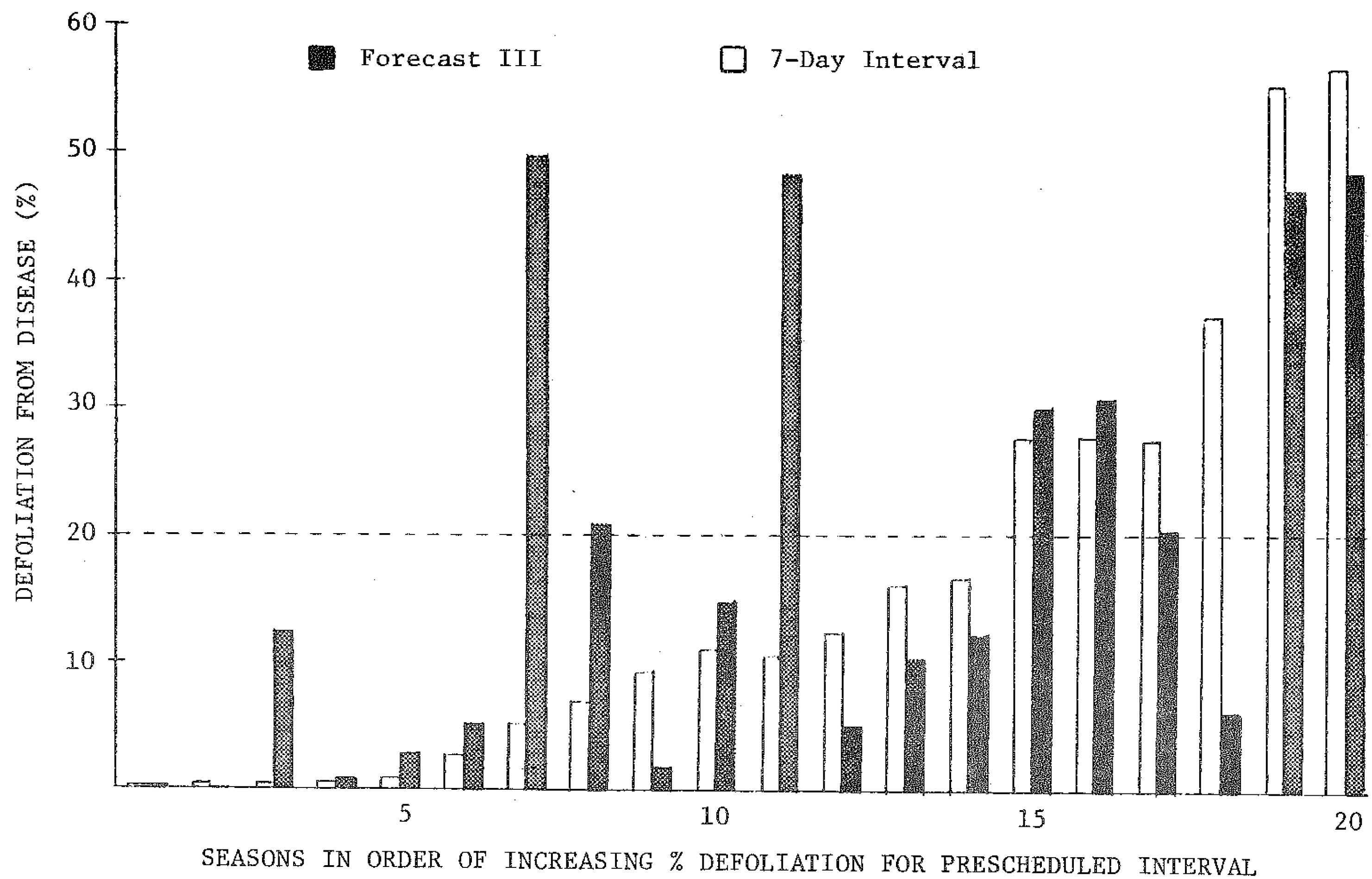
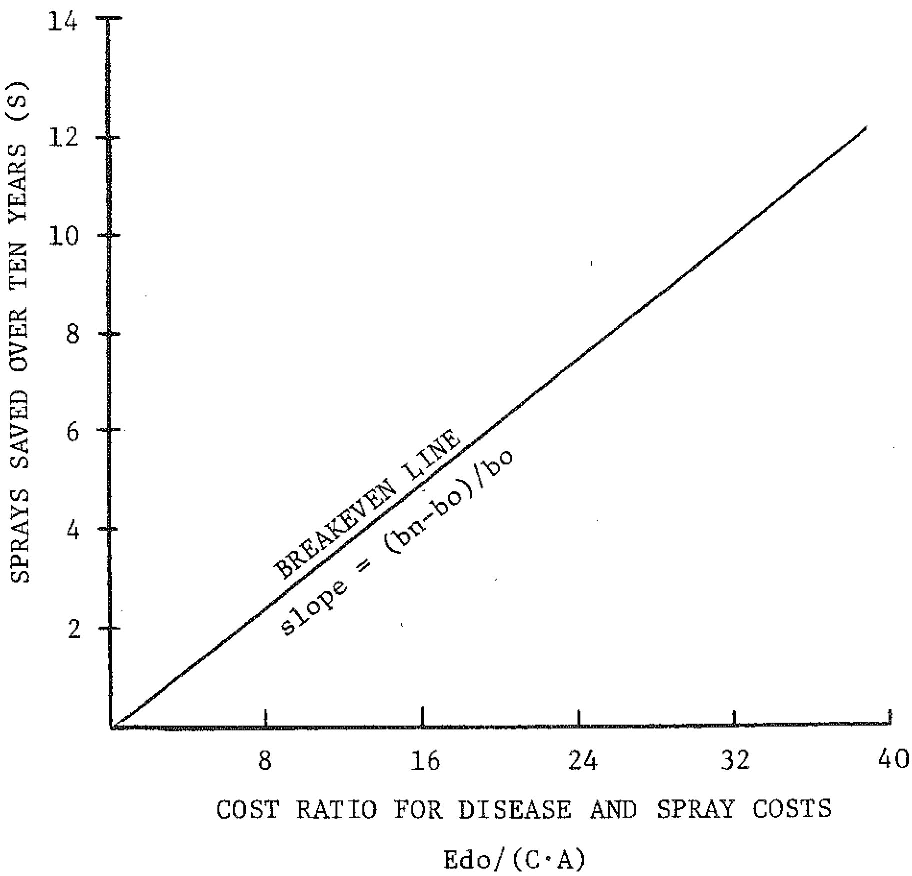


Figure 5. Defoliation from Disease by Season for Forecast III and 7-Day Interval



C = cost per acre of one fungicide spray
A = acres of potatoes on the farm
S = number of sprays the new decision rule must save over 10 years to break even with additional expected cost of disease

Edn = expected cost of late blight over 10 years using the new decision rule
Edo = expected cost of late blight over 10 years using the old decision rule

bn = number of breakdowns in the experiment using the new decision rule
bo = number of breakdowns in the experiment using the old decision rule

The relationship for the breakeven line was derived by noting that at the breakeven point the following equality is true:

$$C\ A\ S = Edn - Edo = (bn / bo)\ Edo - Edo$$
$$C\ A\ S = ((bn / bo) - 1)\ Edo = ((bn - bo) / bo)\ Edo$$
$$S = ((bn - bo) / bo)\ Edo / (C\ A)$$

Figure 6. Breakeven Line for Changes in Expected Disease and Spray Costs

increase in the frequency of breakdowns resulting from changing decision rules. For changing from the seven-day interval to forecast III, the relative increase is (8-6)/6 = 0.33. The x-axis of Figure 6 is the expected cost of late blight over 10 years using the old decision rule divided by the cost of spraying the potato acreage once. This ratio of costs will vary among farms depending on sanitation, seed and cultivar selection, harvesting and storage practices, and climate, and is an index of a farm's suitability for new decision rules. For example, farms for which past losses from late blight are large relative to the size of the farm will have large x values, so adoption of new decision rules that increase likelihood of blight will be advisable for these farms only if the expected savings from reduced spraying are large. Consequently, Figure 6 points out that the choice of a spray decision rule should depend on the characteristics of the farm, and is an example of how this dependency might be incorporated into comparisons of decision rules by considering past infestations of late blight.

This breakeven analysis ignores the costs of information and decision-making needed for forecasting but the inclusion of this cost would simply change the intercept of the breakeven line. More importantly, the analysis ignores the aversion potato growers may have to increasing the probability of large losses even if average income is increased. This risk aversion can be incorporated into the framework presented here by adding a risk premium to Edo or using utility instead of dollars as the scale of measurement.

The analysis using frequency of breakdowns is implicitly based on a dichotomous model of performance: the performance of a decision rule in a season is either adequate, or it is inadequate. Such a model is logical for a disease that farmers try to prevent completely, that can spread rapidly, and that in even small amounts can result in costly changes in management and tuber quality. However, using frequency of disease exceeding a critical value has three important limitations for estimating relative effectiveness and risk of breakdown. First, the critical-value approach requires an empirical or theoretical basis for selecting the critical value. Second, unless the experiment includes a large number of observations, each observation will have a large effect on the estimated ratio of breakdowns, thus increasing uncertainty about the true value of the ratio. Finally, the critical-value approach uses only part of the information contained in the data from the stress test.

Better measures for estimating relative effectiveness and the slope of the breakeven line would use more information from the stress test, and be less sensitive to small changes in the data. For example, the average seasonal ratio of defoliation for the two decision rules uses information about the relative effectiveness of the two rules in individual seasons, and does not require specification of a critical value that sharply divides the data into categories. However, low values may result in extreme ratios (e.g. 1/.01) even though their absolute differences may be insignificant. The average seasonal ratio computed after converting all observations less than 0.10 to 0.10 is a measure of relative effectiveness that combines advantages of both the seasonal ratios and critical-value approach. Using this combined measure[6], the estimated difference in relative effectiveness between forecast III and the seven-day interval is 0.23, compared to 0.33 from the critical-value approach, thus implying a different slope for the breakeven line. Since forecast III did not reduce disease or spraying compared to the seven-day interval, the interval was superior regardless of the slope of the breakeven line.

An Analysis of Breakdowns Occurring with Forecast III

Insights into the relatively poor performance of forecast III compared to prescheduled intervals are provided by comparing severity values calculated for the forecast and severity of disease in simulated unsprayed plots (Figure 7). Severity values are a rating of potential for disease used in forecasting to determine whether to spray. Severity of disease in unsprayed plots indicates how favorable a season actually was for disease. Comparing the two indicates that breakdowns (defoliation from disease exceeding 20 percent) of forecast III were of two types. The first type is represented by observations in the upper-right corner of Figure 7, years in which forecast III broke down despite indicating high favorability for disease and calling for frequent sprays. These four years were very favorable for late blight as measured by the high AUDPC in unsprayed tests. The seven-day interval also broke down in these years.

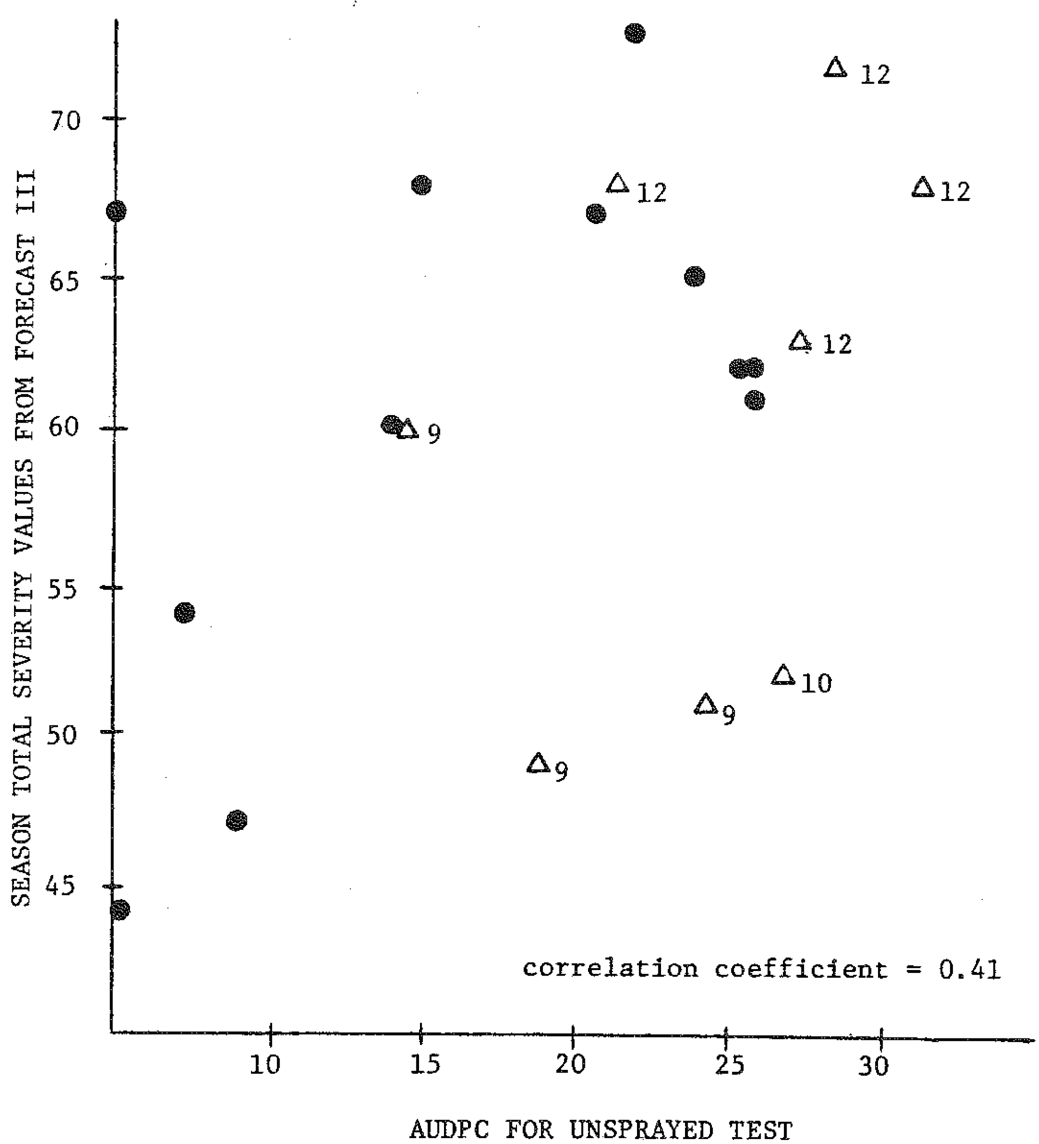
The second type of forecast breakdown occurred when the forecast called for an inappropriately low number of sprays. Three of these breakdowns occurred when total severity values were low relative to AUDPC. These observations, represented in the lower right of Figure 7, suggest that in these years conditions favorable for blight were not fully represented in the calculation of severity values. The seven-day interval broke down only in one of these three years, the one with the highest AUDPC. The fourth forecast breakdown of the second type occurred when only nine sprays were recommended despite high total severity values. Only in one year did forecast III not break down while the seven-day interval did. In that year, 73 severity values were recorded and 12 sprays were recommended. The low correlation (0.41) between severity values and AUDPC reflects the failure of forecast III to gauge precisely the favorability for blight in the simulation model.

CONCLUSIONS

The results of the simulation experiment indicate that when the confounding effects of environment and inoculum are controlled, disease forecasting based on Blitecast does not suppress disease with fewer sprays than prescheduled decision rules. Also, the relative frequency of breakdowns implies that Blitecast (forecast III) does not perform as well as the prescheduled seven-day interval.

These conclusions are contrary to those reported from comparisons in commercial fields in which Blitecast prevented detectable late blight as effectively as prescheduled sprays while requiring fewer applications of fungicide. Infestations of detectable late blight in commercial fields may be uncommon using either decision rule, however, so these comparisons are inconclusive. Also, the cost of fungicide applications is low compared to the large costs that may result from infestations of late blight, so the reported savings from reducing fungicide applications may be insignificant if Blitecast increases the incidence of disease.

The framework introduced in this analysis combines the advantages of stress-test experiments to assess relative effectiveness of decision rules, and farmers' experience or expectations to estimate costs of disease. The framework emphasizes the importance of interpreting results in a manner



● Seasons Forecast III did not break down
(% defoliation < 20%)

Δ Seasons Forecast III did break down
(% defoliation ≥ 20%)

Δ_i i ≡ number of sprays called for by Forecast III
in seasons of breakdown

Figure 7. Relationship among Breakdowns, Severity Values and Disease in Unsprayed Tests

consistent with the experimental model that produces them, and estimating commercial performance of decision rules according to the consequences of disease in commercial fields. The consequences, such as changes in management practices and quality of product, may not be directly related to variables such as percent defoliation measured in stress-test experiments. Also, since the expected consequences of disease may vary among farms, so too may the conclusions about decision rules.

FOOTNOTES

[1]The Weekly Crop Reports of 1961 and 1962 describe evaluations of Wallin's component of Blitecast.

[2]The relationship in the model between weather and microclimate was modified by replacing the specification by Bruhn et al. with a stochastic relationship estimated using hygrothermograph readings obtained for three seasons in experimental plots of potatoes. The estimation was performed by regressing hours of relative humidity above 90 percent on three variables: minimum daily temperature, occurrence of rain on the current day, and occurrence of rain on the previous day. The estimated relationship plus a term representing unexplained variability were used to generate values of hours of relative humidity above 90 percent based on records of temperature and rainfall.

[3]In this simulation experiment, inoculum was present beginning on day 50 of the 120-day season. To minimize the dependence of results on the arbitrary introduction of inoculum, the first fungicide spray was applied on day 50 regardless of the spray interval or forecast being evaluated. All subsequent sprays were made according to the spray decision rule being evaluated. No sprays were applied after day 116 since later sprays would have no effect on observed disease because of the latent period between infection and appearance of lesions.

Since the initial spray for all decision rules was predetermined, only part of Blitecast was evaluated in this experiment. The other part, which forecasts the initial occurrence of late blight and signals for the first spray, was not evaluated here. The simulation model was inadequate for evaluating this part of Blitecast because the results would have been highly dependent on assumptions about inoculum and early stages of disease.

[4]Standard errors indicate the expected variability in sample averages among possible random samples, and are therefore important guides for interpreting results. For estimating variability in sample averages, the standard errors in this simulation experiment are analogous to standard errors calculated from replicates in a field experiment. For the results in Figure 2, the widths of the error bars around average defoliation are large compared to the differences between the prescheduled and forecast response curves. However, since the annual results for different decision rules are linked by their common dependence on the weather (see Figure 5), the precision of comparisons of these decision rules could be increased by paired or blocked comparisons. Pairing and blocking would increase precision by excluding the variability due to differences in weather except as weather affects the difference among decision rules in each season. Consequently, comparisons among individual decision rules could be made with greater precision than suggested by the error bars in Figure 2.

(footnote 4 continued on next page)

The standard errors represented in Figure 2 tend to be smaller for the low sample averages than for the high averages. If the sample averages were to be analyzed using methods for which the variances of averages were assumed equal, then the data could be transformed to adjust for the observed positive correlation between standard error and sample average. For proportions and percentages, the arcsin or angular transformation is commonly used to equalize variances when the sample estimates range from intermediate (30 percent to 70 percent) to near either of the extremes (zero percent or 100 percent), (Snedecor and Cochran).

The data from this simulation experiment were not transformed because the standard deviations from which the standard errors were calculated have additional significance in the experiment beyond their role in estimating the expected variability in averages. The standard deviations indicate the variability in the effectiveness of the decision rules resulting from variability in weather among seasons. Instead of reflecting experimental error or extraneous factors as they might for replicates in a field experiment, the standard deviations in the simulation experiment are important measures of the risk associated with each of the decision rules (Anderson, Dillon, and Hardaker; Halter and Dean).

[5] A breakdown in the stress test does not necessarily imply that the decision rule would have resulted in detectable late blight in commercial fields in that season. A decision rule may be unsuitable for the weather in some seasons, but expression of that unsuitability requires sufficient inoculum to initiate a detectable infestation of late blight. However, if the amount of inoculum when one rule is unsuitable is comparable to the amount when the other rule is unsuitable, then the relative frequency of detectable infestations in commercial fields will be the same as the relative frequency of breakdowns in stress tests.

[6] relative difference in effectiveness =

$$(1/20) \sum_{i=1}^{20} \frac{\max(f_i,10) - \max(p_i,10)}{\max(\min(f_i,p_i),10)}$$

f_i = % defoliation in season i using forecast III
p_i = % defoliation in season i using seven-day interval

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Appendix A

ANNUAL SUMMARIES OF REPORTS OF LATE BLIGHT IN UPSTATE NEW YORK

Annual Summaries of Reports of Late Blight
Upstate New York, 1960-1980

Year	Date of 1st Report	Reported Incidence*	Reported Severity**	Comments
1980	---	none	---	preseason reports of late blighted tubers in storage and cull piles
1979	August 13	rare	mild	
1978	August 14	rare	mild	single report that late blight appeared in "a few areas"
1977	August 22	common local	mild	common in one small area; 10-day spray interval implicated in one occurrence
1976	July 19	common general	severe	plentiful inoculum; sprays delayed by rain; one 40 acre field a total loss; control measures checked disease elsewhere
1975	July 14	common local	mild	common in one small area; control measures checked disease
1974	August 12	common local	severe	fungicides in short supply; severe disease reported for two fields
1973	August 6	common local	mild	preseason reports of late blighted seed; noncertified seed, irrigation, low-pressure sprayer implicated in occurrence
1972	August 7	common general	severe	sprays delayed by rain
1971	---	none	---	
1970	---	none	---	found in one cull pile
1969	July 28	common general	severe	common in late August in western New York; storage problems expected
1968	August 12	rare	mild	only occurrence on low-lying field with 10-day spray interval

continued

Year	Date of 1st Report	Reported Incidence*	Reported Severity**	Comments
1967	August 7	rare	mild	only occurrence on unsprayed field
1966	---	none	---	reports virtual absence of late blight in past several years
1965	---	none	---	
1964	---	none	---	early blight on fields sprayed according to forecasts of late blight
1963	August 26	rare	mild	late blight in one field; satisfactorily controlled despite extremely favorable weather for blight
1962	---	none	---	
1961	August 7	common general	mild	widespread scattering of blight but no severe outbreak
1960	August 8	common local	severe	severe defoliation in one field

Source: Weekly Report on Insects, Diseases, and Crop Development, Cooperative Extension, Cornell University, Ithaca, New York 14853-0398.

*Reported Incidence

none: no reports of late blight in commercial fields

rare: only one reported occurrence of late blight in commercial fields

common local: late blight reported in more than one field, but confined to a few locales

common general: late blight reported as being common throughout all or most of upstate New York

**Reported Severity

mild: no indication of significant crop losses

severe: indication of significant crop losses in at least one field

Appendix B

THE CHARACTERISTICS OF FIELD EXPERIMENTS USED TO STUDY LATE BLIGHT

The results of field experiments on late blight reflect the conditions under which they are performed. The size of experimental plots is one aspect of the experimental conditions that affect results. Plot size is limited by availability of land, and the time required to manage plots and inspect foliage for disease. Because of these limitations, small plots (e.g. 20 square meters) are commonly the unit of observation for studies of late blight. Observation of disease in these plots provides information about development of disease within primary sites of infection, but usually none about the spread of disease from primary to secondary sites in a field.

Without the presence of inoculum to initiate the disease, comparisons of treatments intended to control it cannot be performed. Also, differences in the amount of initial inoculum to which potato plots are exposed could confound treatment effects. Consequently, to insure that inoculum is present in adequate and comparable amounts in all plots, experimenters introduce inoculum into the experimental area rather than rely on uncontrolled, exogenous sources. By insuring presence and uniformity of inoculum, the experimenter increases the amount of information from the experiments about the effect of the treatments on the disease, but precludes inferences about the abundance of naturally occurring inoculum and resulting infections.

The development of the late blight pathogen is highly dependent on microclimate. If the microclimate of the experimental area is unfavorable for the pathogen, then the effect of the treatments will be difficult to assess because microclimate rather than treatments will be the principal controlling factor. To insure that treatments rather than microclimate are the controlling factor, experiments may be conducted in locations with microclimates favorable for the pathogen. Also, the favorability of the microclimate may be enhanced by the experimenter, such as with sprinklers to extend the periods of leaf wetness. The results of experiments in these conditions reflect the performance of the treatments in locations favorable for the pathogen, but are not direct indications of performance in other locations.

In addition to making treatments the controlling factor, a favorable microclimate for the pathogen increases disease and thereby reduces the effect of measurement error in the assessment of disease. Although the absolute magnitude of measurement error is likely to increase as disease increases, the increase is probably less than proportional to the increase in disease. By experimenting at higher disease, the treatment effects may increase relative to measurement error, and comparisons among treatments may be more meaningful.

In summary, field experiments for studying late blight often are performed with small plots, each representing an individual focus of disease initiated by plentiful inoculum and intensified by a favorable microclimate. These experiments gauge the relative effectiveness of treatments, but are not representative of commercial potato fields. In effect, the experiments provide a stress-test comparison of treatments. This method of testing is analogous to tests of the strength of materials or durability of machines in which an experimenter subjects them to extreme conditions, noting the duration and levels of stress withstood prior to breakdown. This approach may provide more information than much longer periods of observation under more common conditions. Similarly, an experimenter can learn more about the effectiveness of treatments against late blight if inoculum and favorable conditions insure that effectiveness is actually tested and differences in effectiveness are enhanced.